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Capacity Evaluation of a MEMS Based Micro Cooling Device Using Liquid Metal as Coolant

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Abstract**—The latest generation of gigahertz-clock-rate CPUs is becoming more challenging to fit into designs. These chips are squeezing into tighter and tighter spaces with no enough places for heat to dissipate. Meanwhile, high-capacity cooling options remain limited for many small-scale applications such as micro-systems, sensors and actuators, and micro/nano electronic components. This work presents a MEMS based micro cooling device, which is comprised of an active cooling substrate embedded with fluidic cooling functionality using liquid metal, to provide direct cooling to high heat flux electronics and MEMS devices. In order to better understand the cooling capability of this MEMS-based micro cooling device, the three-dimensional heat transfer process thus involved was numerically simulated. A series of calculations with different flow rates and thermal parameters were performed. Effect of different working fluids is also investigated. The results indicate that the MEMS-based cooling device has powerful cooling capability while using liquid metal as cooling fluid, and thus allow for lower operating temperatures for electronic devices and micro/nano systems.**

Keywords-chip cooling; MEMS; liquid metal; high heat flux; numerical simulation

I. INTRODUCTION

Thermal management has been a major concern in packaging of micro/nano systems. In the last several years, higher transistor integration densities, faster electronic chips and drastic increases in performance have occurred [1]. Such increased power consumption of advanced microelectronic devices coupled with more and more compact packages result in critical demands on thermal management. It is expected that heat flux levels in excess of 100 W/cm^2 for commercial electronics and over 1000 W/cm^2 for selected military high power electronics will soon become a realistic challenge to overcome [2-4]. There is also a growing demand for more sophisticated electronics used in harsh environment applications. Therefore, conventional air-cooled designs may no longer be able to remove these heat fluxes and, for a number of applications, direct air-cooling will have to be replaced or supplemented by other high performance compact cooling techniques.

Currently, the major limitation for the development of more compact electronic and MEMS devices is due to the lack of an efficient technique to remove heat from these devices. To overcome this limitation, many thermal management methods have been developed such as using liquid immersion cooling [5,6], the micro-channel sink with liquid as the working fluid [7], jet impingement [8], thermoelectric cooling [9,10], heat pipe [11,12], and even miniaturized refrigeration system [13]. However, the present applications with high power dissipation densities are requiring cooling beyond what can be offered by most of these thermal management schemes. In addition, most of such types of structures are too large for many applications including certain electronic components, sensors, and MEMS/NEMS devices.

MEMS-based micro cooling devices have found some success here, but the key missing element has been a practical means of removing the heat. In terms of power consumption, the past Intel 486 processor is about 2 W, and the current Pentium 4 processor is about 100 W [14]. The power will climb up with time. To meet this demand, it is preferred if the working fluid of MEMS-based micro cooling device could have high evaporating temperature and high thermal conductivity. In this sense, liquid metal looks as a perfect candidate [4, 15]. Starting from this point, Liu and Zhou [15] proposed for the first time the method of using the low melting point metal such as liquid gallium and its alloys as the cooling fluid to cool the electronic devices in 2002.

In this study, a MEMS-based micro cooling device using liquid metal as working fluid is presented. In order to better demonstrate the cooling capability of liquid metal in this MEMS-based cooling device, a newly developed numerical algorithm [16, 17] is extended to simulate the corresponding heat transfer process involved in both the liquid metal and the substrate areas. The theoretical efforts made in this study are aimed to obtain the first demonstration of the capacity of a MEMS based micro cooing device which uses liquid metal as coolant.

II. MATHEMATICAL MODEL AND ALGORITHM

Fig. 1 depicts a schematic of MEMS-based micro cooling module (made by metal with high thermal conductivity such as aluminum and copper), in which the chip device contacts with the cooling module at x=0. The computation domain is prescribed in a rectangular geometry with 4 mm,10 mm and 10 mm in x, y and z directions respectively, and the dimension of the chip device which is located at the center of surface x=0 is 5*5 mm^2. The cooling module uses a pump-driven liquid coolant that flows through its 100 μm wide micro-channel, and the fluid pumping can be driven by electromagnetic pump or electrokinetic pump. Consequently, the whole domain consists of heat conduction and heat convection domains. The central lines of this micro-channel are (x=0.002 m, y=0.002 m, $0\le z \le$ 0.008 m) $\cup$ (x=0.002 m, 0.002 m$<y\le$ 0.004 m, z=0.008 m) (x=0.002 m, y=0.004 m, 0.002 m$< z \le$0.008 m) $\cup$ (x=0.002 m, 0.004 m$<y\le$ 0.006 m, z=0.002 m) $\cup$ (x=0.002 m, y=0.006 m, 0.002 m$< z \le$0.008 m) $\cup$ (x=0.002 m, 0.006 m$<y\le$ 0.008 m, z=0.008 m) $\cup$ (x=0.002 m, y=0.008 m, $0\le z <$0.008 m).

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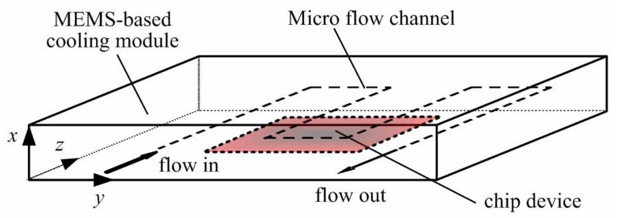


Figure 1. Schematic of MEMS-based cooling module

For the heat conduction domain, thermal equation is described by Fourier's law

$$\rho c \frac{\partial T(\mathbf{X},t)}{\partial t} = \nabla \cdot k \nabla \left[T(\mathbf{X},t) \right], \quad \mathbf{X} \in \Omega_1 \tag{1}$$

where ρ , c and k are the density, specific heat and thermal conductivity of the cooling module, respectively; $\mathbf{X}$ contains the Cartesian coordinates x , y and z ; and Ω_1 denotes the heat conduction domain.

For the convection domain, the temperature of cooling fluid in micro flow channel, which varies along the flow direction, is governed by the convective heat transfer equation [4]. For the flow channel along y axis, the thermal model reads as

$$\rho_f c_f \frac{\partial T}{\partial t} = k_f \frac{\partial^2 T}{\partial z^2} + \frac{hP}{S}\left(T_w - T\right) - \rho_f c_f v \frac{\partial T}{\partial z}, \quad \mathbf{X} \in \Omega_2 \tag{2}$$

and for the flow channel along z axis, the thermal model reads as

$$\rho_f c_f \frac{\partial T}{\partial t} = k_f \frac{\partial^2 T}{\partial z^2} + \frac{hP}{S}\left(T_w - T\right) - \rho_f c_f v \frac{\partial T}{\partial z}, \quad \mathbf{X} \in \Omega_2 \tag{3}$$

where ρ_f, c_f and k_f are the density, specific heat and thermal conductivity of the cooling fluid, respectively; $h = Nu \cdot k_f / D$ is the convective heat transfer coefficient between the fluid and cooling module; D, P and S are the diameter, perimeter and cross-sectional area of the channel; v is the mean flow velocity; Nu the Nusselt number; T_w the wall temperature of the channel; and Ω_2 denotes the convection domain. The sign of velocity v is assigned as positive, i.e., the velocity of cooling fluid flowing along the positive direction of y and z axes is positive and otherwise minus.

The initial condition is defined as uniform temperature of 25 °C over the whole area. The boundary conditions is prescribed as

$$\begin{cases} -k\dfrac{\partial T}{\partial x} = \begin{cases} q_c & \text{area contacting with chip device} \\ 0 & \text{other area} \end{cases} & \text{at } x = 0 \\ -k\dfrac{\partial T}{\partial n} = h_a (T - T_a) \quad \text{at other boundaries} & \end{cases} \tag{4}$$

where $q_c = P_c / S_c$ is the heat flux of chip device; P_c and S_c are the power and surface area of chip device, respectively; h_a is the convection heat transfer coefficient between the cooling module and its surrounding air; and T_a is the surrounding air temperature.

Considering that Monte Carlo (MC) method can solve the temperatures at any desired positions independently from the solutions at other points and is timesaving, the MC algorithm developed in our previous works [16, 17] is extended to simulate the heat transfer problem involved in micro-channel cooling in this study. The description and derivation of MC algorithm are omitted here for brevity. Readers are referred to [16, 17] for more details.

III. RESULTS AND DISCUSSION

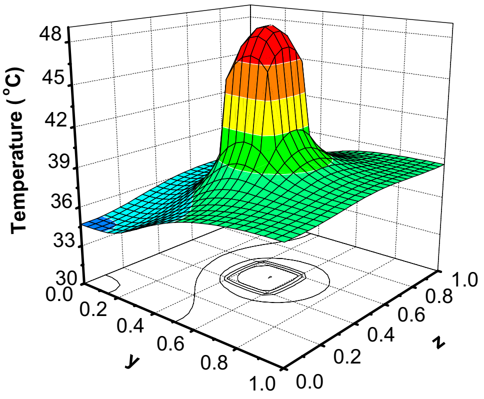
As a routinely used cooling fluid, the liquid metal must satisfy the following requests: non-poisonous, non-caustic material, low viscosity, high thermal conductivity and heat capacity. Liquid gallium offers an attractive solution, and it is thus selected in this study.

In calculations, the fluid temperature at the inlet is prescribed as 30 °C, considering that the melting point of gallium is 29.7 °C [18]. The constant Nusselt number is taken as $Nu = 7$ [4], and $h_a = 10 \text{W/m}^2 \cdot ^\circ\text{C}$, $T_a = 25^\circ\text{C}$. The thermal properties used in this study are summarized in Table I. The computer code compiled in this article is revised from the code developed in our previous study [17], which had been validated.

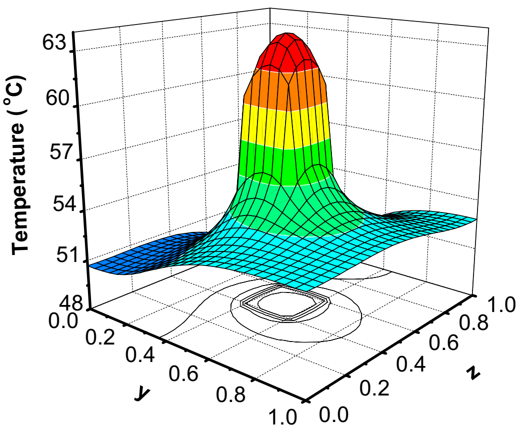
Fig. 2 shows the temperature distributions at the surface between chip device and cooling module (i.e., x=0) under different cases, in which the cooling module is made by metal of copper, and the heat flux of chip device is 70 W/cm^2. It can be seen from Fig. 2 that as expected, the cooling performance of the liquid gallium is much better than that of the water. It also indicated that the larger the flow rate, the better the cooling performance. Moreover, comparing Fig. 2(a) with Fig. 2(c) and Fig. 2(b) with Fig. 2(d), it can be found that for the cases using water as cooling fluid, the lowest temperature of cooling module does not appears in the vicinity of flow inlet while it does for the cases of gallium. The reason for this phenomenon is that the low thermal conductivity of water does not allow energy to efficiently transfer from the solid heat transfer surfaces of the source to the cooling fluid, and then resulting in that the lowest temperature appears at the first curve location of the fluid channel. It further indicates that as a cooling fluid, liquid gallium is much attractive for high power density device cooling primarily due to its high thermal conductivity, as compared with water.

TABLE I. SUMMARY OF THE THERMOPHYSICAL PROPERTIES [18,19]

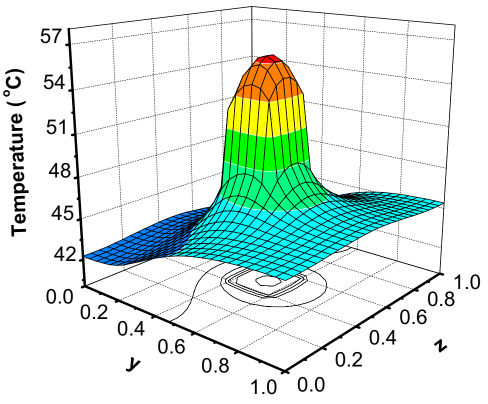
Parameters	**Materials**			
	Aluminum	***Copper***	***Gallium***	***Water***
ρ (kg/m^3)	2710	8930	6093	998
c (J/kg·°C)	902	386	3440	4183
k (W/m·°C)	236	398	29.4	0.599



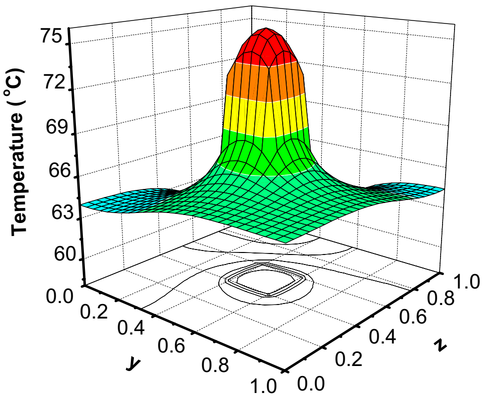
(a) liquid gallium as cooling fluid, v=0.8 m/s



(b) water as cooling fluid, v=0.8 m/s



(c) liquid gallium as cooling fluid, v=0.4 m/s



(d) water as cooling fluid, v=0.4 m/s

Figure 2. Temperature distributions at x=0, t=600 s

Fig. 3 gives the transient responses of temperatures at the center of heating surface and the outlet of fluid, in which the cooling module is made by metal of copper, and the heat flux of chip device is 70 W/cm^2. It further indicated from Fig. 3 that the cooling performance of the liquid gallium is much better than that of the water.

In order to investigate the effect of thermophysical properties of cooling module on its cooling performance, numerical simulation for the case of cooling module made by aluminum is also performed. For convenience of comparison, other parameters are taken as the same in the corresponding calculations. The results are depicted in Fig. 4, in which the results for the cases of cooling module made by aluminum and copper are included together. It is indicated that the cooling performance of the system will obtain significant enhancement, if the cooling module is made by material with high thermal conductivity such as copper.

All of the above calculations are based on a relative low thermal load (q_c =70 W/cm^2). In fact, there is a growing demand for more sophisticated electronics with high thermal load used in harsh environment applications. To further investigate the capability of MEMS-based cooling module using liquid gallium as working fluid, transient temperatures at the center of heating surface under different thermal loads are computed and the results is presented in Fig. 5. It is clearly shown that even under the extreme thermal load (q_c =210 W/cm^2), the maximum temperature is still below 100 °C. This indicates again that the MEMS-based cooling device presented in this study has strong capability for extreme cooling needs.

One of the most critical issues in the electronic industry is the thermal management of electronic devices, especially meeting the limitations on maximum operating temperature and ensuring temperature uniformity across the chip. We have also observed that the results presented in Fig. 2 have not shown good uniformity across the chip. In addition, the difference between temperatures at the center of heating surface and the outlet of fluid (shown in Fig. 3) is not small enough. These results indicate that, the heat dissipation effect is

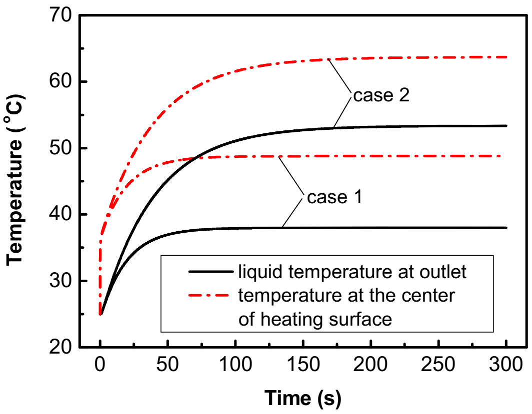


Figure 3. Transient temperatures at the center of heating surface and the outlet of fluid. Case 1 - gallium as cooling fluid, and *v*=0.8 m/s; Case 2 - water as cooling fluid, and *v*=0.8 m/s

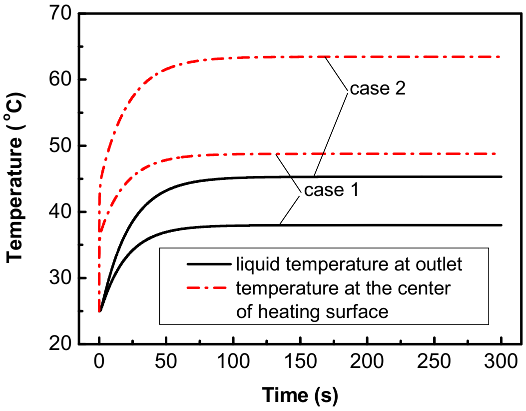


Figure 4. Transient temperatures at the center of heating surface and the outlet of fluid (*v*=0.8 m/s, gallium as cooling fluid). Case 1 - cooling module made by copper; Case 2 - cooling module made by aluminum

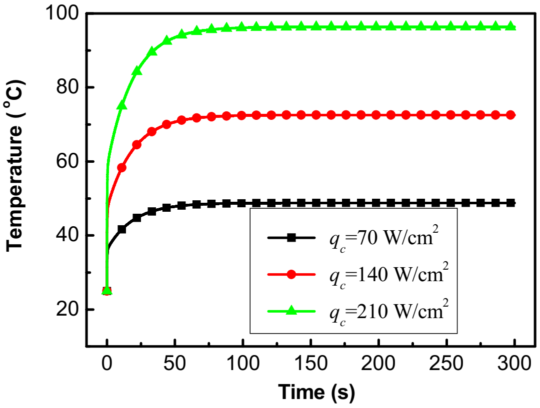


Figure 5. Transient temperatures at the center of heating surface under different heat fluxes of chip device (*v*=0.8 m/s, gallium as cooling fluid)

still not the best. In order to obtain optimal results, optimizing the structure and position of micro fluid channel is needed. This feature needs many additional works in the future.

IV. CONCLUSIONS

The performance and capability of a MEMS-based cooling device, which uses liquid metal as cooling fluid flowing through its micro-channels, has been numerically investigated in this study. The results indicate that the liquid metal has powerful cooling capability, which is much better than that of the conventional water based cooling system. The results also suggest that the MEMS-based cooling device using liquid metal as working fluid has potential applications for future microelectronics or MEMS type devices. Due to its excellent heat transfer performance, liquid metal will provide a possible solution for extreme cooling needs such as sophisticated electronics with extremely high thermal load used in harsh environment applications in the near future. To obtain optimal cooling results when using liquid metal based micro cooling device, the structure of micro flow channel presented in this study still needs to be further optimized.

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